Shallow-Water Propagation

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LONG-TERM GOALS

Develop propagation models and related methods for complex shallow-water environments, test their capabilities and accuracy, and apply them using environmental and acoustic data.

OBJECTIVES

(A) Treat propagation through range-dependent elastic and poro-elastic sediments, in waveguides of variable overall thickness, and with pulse or broadband sources.
(B) Find field statistics efficiently from stochastic propagation models, quantify effects of random environmental and experimental variability, and use model predictions to analyze data.

APPROACH

(A) We apply high accuracy PE techniques, incorporating energy conservation and causality corrections, to isotropic and anisotropic sediments and to regions with large topographical variations. Simulated annealing inversion techniques are employed for parameter estimation.
(B) We construct stochastic ensembles of geoacoustic and ocean variability using data samples and representations by empirical orthogonal functions. Field calculations are performed by PE and normal mode methods.

- Principal collaborators are: Rensselaer graduate students and former students; Dr. Michael Collins (NRL), in model development; and Dr. Mohsen Badiey (Delaware), Dr. William Carey (BU/NUWC), and Dr. James Lynch (WHOI), in modeling and analysis of experimental data.

WORK COMPLETED

(A) We completed testing and benchmarking our PE model [1] which handles depth and range variability of elastic sediments with transversely isotropic (TI) geoacoustic properties. With the help of a coordinate rotation method, we began a series of estimates [2] of the resolvability of the directionally dependent TI wave speeds. We improved the ease and range of applicability of an initial model formulation [3] for TI poro-elastic sediments. We applied novel hybrid (normal mode and PE) models to three-dimensional propagation in shallow, coastal, and near-island waveguides where the effective thickness changes significantly [4]. An energy conserving extension that uses conformal mapping to simplify cross-sections for these waveguides [5] was tested on new examples. We employed the Kramers-Kronig relationship to determine dispersive effects in a pulse propagating over an elastic sediment with frequency-dependent attenuation [6].

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 1999**	2. REPORT TYPE	3. DATES COVERED **00-00-1999 to 00-00-1999**
4. TITLE AND SUBTITLE **Shallow-Water Propagation**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Rensselaer Polytechnic Institute,Troy,NY,12180-3590**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

This investigation takes advantage of how we treated propagation from a strong pulse source over a fluid bottom [7] with this type of attenuation.

(B) We used our approach for efficient modeling of random ensembles, applied to sediment sound speed variability in the AGS region, for new predictions [8] of intensity statistics. We completed calculations of wave number statistics due to fluctuations of sediment layer depths and sound speeds along tracks of the AGS95 experiment [9]. Additional statistics of broadband intensity fluctuations were found from PE calculations in order to compare with data from all tracks of the AGS92 experiment [10]. We used both adiabatic normal mode and PE approximations to model the behavior of transmission loss and horizontal coherence for the environment of the ACTIII experiment [11]. These calculations took advantage of procedures that we used [12] for estimating horizontal and vertical coherence arising from small fluctuations in the ocean and sediment volume and in layer interface heights.

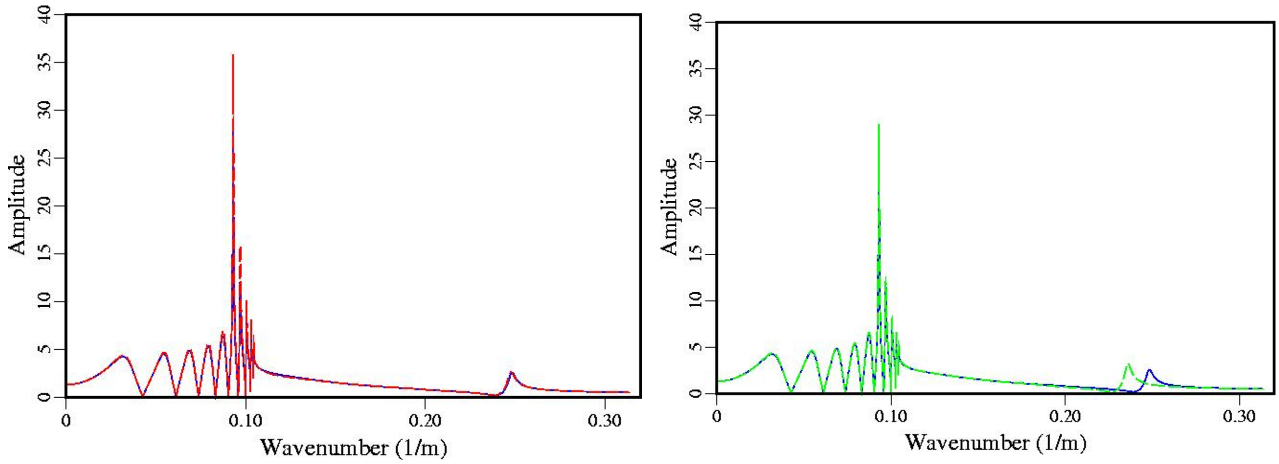
RESULTS (from three selected investigations)

- Because anisotropy can arise in sediments when they form and as they evolve, we developed and tested a PE model to handle range-dependent propagation over transversely isotropic layers. These types, which are typical for ocean sediments, require four speeds to specify two-dimensional acoustic waves: the larger speeds c_{pr} and c_{pz} for waves traveling in horizontal and vertical directions, the smaller speed c_{srz} for waves traveling in either horizontal or vertical directions, and the extreme value c_{se} of the smaller speed. A natural question is whether a given anisotropic environment has a corresponding "effective" isotropic environment (with wave speeds c_p and c_s) that leads to essentially the same acoustic results in the water. Using PE simulations and inversion calculations, we conclude that depending on the anisotropic parameters, an "effective" isotropic environment may or may not exist. An example of the latter case is the environment described below Fig. 1; the former is illustrated by the same environment with c_{pz} = 1750 m/s.

- Many measurements have shown frequency dependence of attenuations in elastic and poro-elastic sediments, and the dependence is linear in the absence of relevant attenuation length scales. As a consequence, causality by means of the Kramers-Kronig relationship imposes a frequency dependent adjustment to the wave speeds, which in turn produces dispersion in broadband signals. We developed a broadband version of an elastic PE model, accounted for the physically required dispersion, and examined dispersive effects on pulse propagation. Based on a variety of range independent and range dependent environments, we conclude that sediment attenuation and dispersion can be treated efficiently and that distinct components of propagating pulses can be affected differently by these mechanisms. The example in Fig. 2(b) illustrates pulse shape and arrival time differences that result from linear frequency dependence of attenuations.

- We have determined and tested procedures for approximating coherence lengths when environmental volume and interface variations are relatively small and have horizontal correlation lengths longer than a wavelength. Difficulties in obtaining coherence lengths from data can complicate comparisons with model predictions, but estimates had been found from signal gain characteristics during the ACT III experiment in the Strait of Korea. We found that modeling mean transmission losses at that site required a nonlinear power law frequency dependence of the attenuation in the upper sediment layer. We also conclude that this attenuation behavior makes a significant difference in the values of coherence lengths for all but the highest experimental

frequency. The estimates shown in Fig. 3(b) correspond generally to those derived from the ACT III measurements as well as to those extracted from data at other sites.



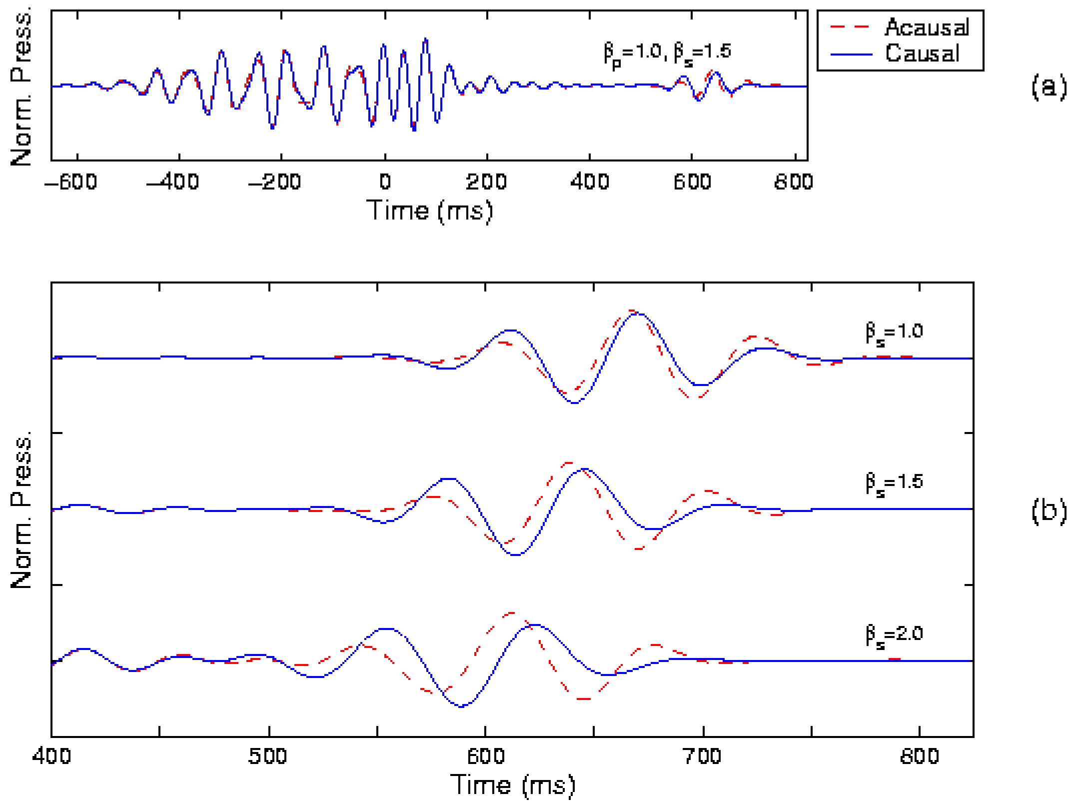
***1*. Benchmark environment A consists of water (c_w = 1500 m/s, d_w = 300 m) overlying a TI elastic layer ([c_{pr}, c_{pz}] = [1700, 1650] m/s, [c_{srz}, c_{se}] = [800, 850] m/s, [β_p, β_s] = [0.2, 0.4] dB/λ, ρ = 1.5 g/cm^3, d = 1200 m), with f = 25 Hz, z_s = 295 m. (*Left*) Wave number spectra for A (solid blue) and an isotropic (c_p = 1700 m/s, c_s = 812 m/s) environment B (dashed red) that produces wave number locations very close to those of A, but amplitude peaks are mismatched, causing significant intensity differences. (*Right*) Wave number spectra for A (solid blue) and an isotropic (c_p = 1700, c_s = 850 m/s) environment C (dashed green) that produces amplitude values very close to those of A, but the interface wave number location near 0.25 /m is shifted. No isotropic elastic medium exists that produces the same acoustic results as this anisotropic environment.**

IMPACT/APPLICATIONS

New capabilities for treating and appraising the influences of sediment anisotropy and dispersion will be available for propagation predictions and data analyses. It will be possible to handle interactions of ocean acoustic signals with beach or island topography. Efficient specification of intensity and coherence statistics that arise from environmental fluctuations and experimental variability will be feasible. Extended inversion procedures will be capable of producing estimates of parameters characterizing geoacoustic anisotropy and coherence lengths.

TRANSITIONS

Results are being used for modeling and comparisons with data from several series of experiments (HCE, AGS, ACT) that are aimed in part toward improving sonar systems in shallow water. Implementations of new propagation models and interpolation techniques have been distributed.



2. Shallow water (c_w = 1500 m/s, d_w = 100 m) overlies an elastic layer (c_p = 2400 m/s, c_s = 1200 m/s, ρ = 1.5 g/cm^3, d = 800 m) with attenuations that linearly increase with frequency (constant dB/λ values are shown), and with a Gaussian pulse source (f_{center} = 20 Hz, τ = 60 ms, z_s = 90 m). Time series of normalized pressure at z_r = 90 m have causal dispersion from the Kramers-Kronig relationship included (solid blue) or not included (dashed red). (a) Full time series at R = 2 km show early wave arrivals due to bottom compressional energy, water borne energy arriving near (relative) time zero, and a late interface wave arrival. (b) While dispersion in the early arrivals is due only to β_p, dispersion in the interface wave increases with β_s and produces both distortions in the pulse shape and faster arrival of its energy.

RELATED PROJECTS

- Additional research with Dr. Michael Collins (NRL) includes development [13] of an energy conservation requirement for elastic PE propagation over a broad wave number spectrum; construction [14] of a wave number spectral solution that conserves energy between range independent regions; derivation [15] of a PE model for oceanic internal gravity waves and atmospheric acousto-gravity waves; and development and application [16] of a hybrid model that accounts for influences of horizontal ambient flows on propagation of internal gravity waves.

- Research with Dr. William Carey (BU/NUWC) and Dr. James Lynch (WHOI) includes extensions and applications of ongoing work [11], [12] on coherence in shallow water waveguides.

- Additional research with Dr. Mohsen Badiey (Delaware) includes demonstrating [17] that azimuthally coupled propagation can arise from the heterogeneity of shallow coastal sediments.

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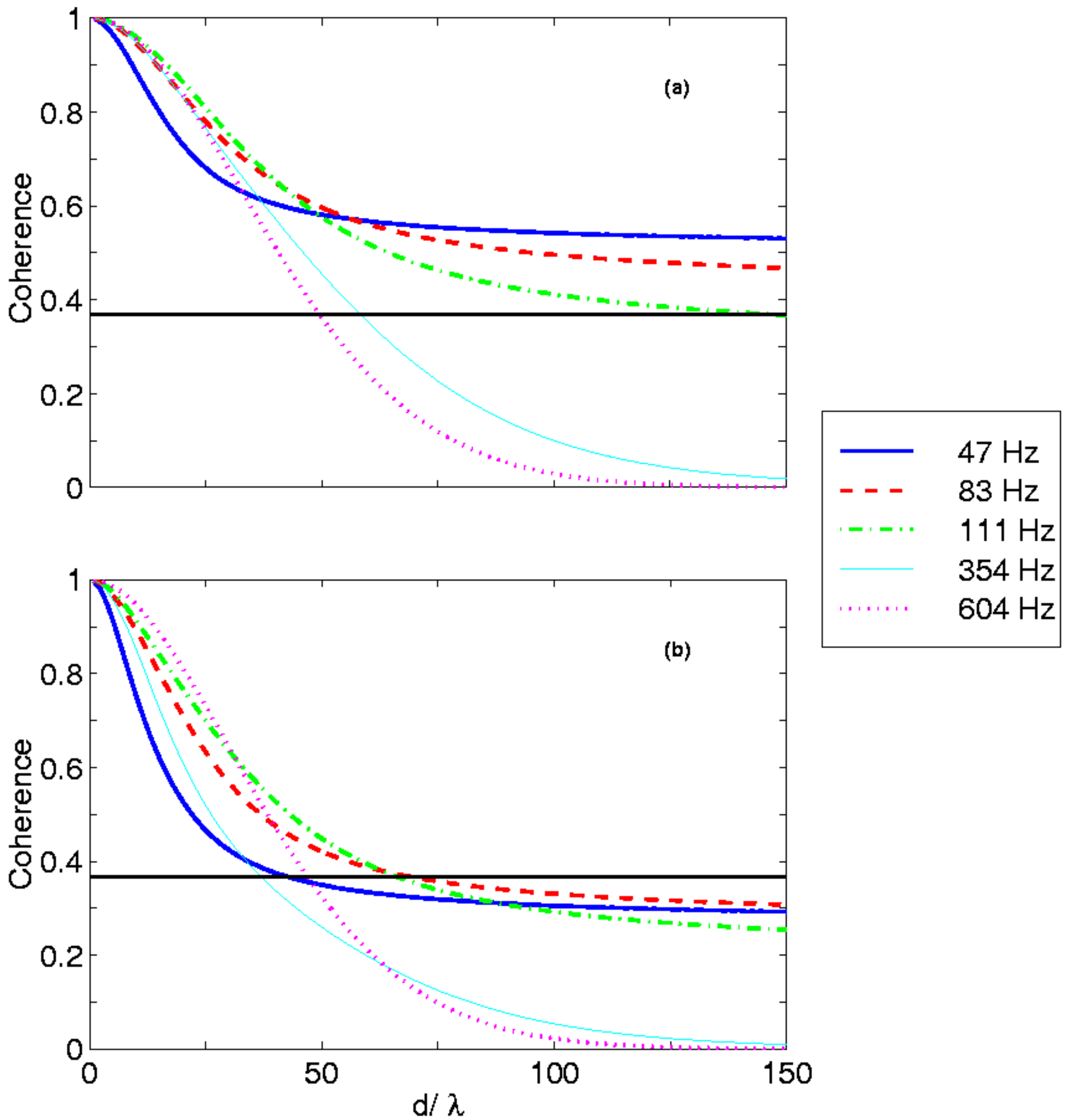

3.Horizontal coherence versus receiver separation in wavelengths at range 30 km, for five frequencies of the ACT III experiment. Ocean SSPs and bathymetry data along with a core based, four-layer geoacoustic model specify the mean environment. Random volume fluctuations in the ocean and sediment, and on the ocean surface and sediment interfaces, have Gaussian correlation functions. The upper sediment layer attenuation is modeled with frequency dependence that is (a) linear, or (b) nonlinear, with power exponent determined by fitting trends in transmission loss data. The 1/e criterion (solid line) specifies coherence lengths, which for the four lowest frequencies are affected by the attenuation frequency behavior. Coherence lengths from (b) are between 30 and 70 wavelengths and agree with generally observed values at this site and elsewhere.

REFERENCES

[1] A. J. Fredricks, W. L. Siegmann, and M. D. Collins, “A parabolic equation for anisotropic elastic media,” accepted for publication in Wave Motion.

[2] A. J. Fredricks, W. L. Siegmann, M. D. Collins, and J. F. Lingevitch, “Estimation of anisotropic sediment parameters,” (A) J. Acoust. Soc. Am. **106**, 2132, (1999).

[3] A. J. Fredricks, W. L. Siegmann, and M. D. Collins, “Parabolic equation models for poro-elastic transversely isotropic sediments,” (A) J. Acoust. Soc. Am. **103**, 2857 (1998).

[4] R. A. Coury, M. E. Bystrom, M. D. Collins, and W. L. Siegmann, “Three-dimensional effects on acoustic propagation in waveguides of variable thickness,” Fourth Int. Conf. On Theoretical and Computational Acoustics (May 1999).

[5] R. A. Coury, W. L. Siegmann, and M. D. Collins, “Acoustic propagation in waveguides of variable thickness,” submitted for publication.

[6] W. Jerzak, R. S. Kulkarni, W. L. Siegmann, and M. Collins, “Attenuation and dispersion in pulse propagation over an elastic sediment,” (A) J. Acoust. Soc. Am. **106**, 2225 (1999).

[7] R. S. Kulkarni, W. L. Siegmann, M. D. Collins, and B. E. McDonald, “Nonlinear pulse propagation in shallow water environments with attenuating and dispersive sediments,” J. Acoust. Soc. Am. **104**, 1356-1362 (1998).

[8] M. Jaye, W. L. Siegmann, and M. Badiey, “Geoacoustic profile estimation using empirical orthogonal functions,” accepted for publication in J. Ocean Eng.

[9] M. J. Longfritz, W. L. Siegmann, M. Badiey, and M. J. Jacobson, “Estimating horizontal wave number variations in stochastic shallow-water channels,” submitted for publication.

[10] M. Jaye, M. Badiey, and W. L. Siegmann, “Broadband propagation over randomly varying, range-dependent elastic sediments,” (A) J. Acoust. Soc. Am. **103**, 2858 (1998).

[11] I. Rozenfeld, W. M. Carey, P. G. Cable, and W. L. Siegmann, “Geoacoustic and signal gain modeling in a range-dependent, shallow water environment,” (A) J. Acoust. Soc. Am. **106**, 2132 (1999).

[12] I. Rozenfeld, W. M. Carey, J. F. Lynch, P. Cable, and W. L. Siegmann, “Spatial coherence in range-dependent shallow water environments,” (A) J. Acoust. Soc. Am. **103**, 2856 (1998).

[13] M. D. Collins and W. L. Siegmann, “A complete energy conservation correction for the elastic parabolic equation,” J. Acoust. Soc. Am. **104**, 687-692 (1999).

[14] M. D. Collins, H. Schmidt, and W. L. Siegmann, “An energy-conserving spectral solution,” submitted for publication.

[15] J. F. Lingevitch, M. D. Collins, and W. L. Siegmann, “Parabolic equations for gravity and acousto-gravity waves,” J. Acoust. Soc. Am. **105**, 3049-3056 (1999).

[16] M. D. Collins, B. E. McDonald, W. A. Kuperman, and W. L. Siegmann, “Parabolic equation modeling of azimuthally advected gravity waves,” accepted for publication in Wave Motion.

[17] X. Tang, M. Badiey, and W. L. Siegmann, “Azimuthal coupling of shallow water sound propagation due to anisotropic sediment layers,” submitted for publication.

PUBLICATIONS

- Published: [6], [13], [15]
- Accepted: [1], [8], [16]
- Submitted: [5], [9], [14], [17]